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Implications of a model with a longer tau lifetime

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ABSTRACT

It is possible that the tau lepton may have a longer lifetime than that predicted by the standard model. The simplest extension to the standard model incorporating a longer tauon lifetime involves the addition of a gauge singlet Weyl fermion. We consider the most general model of this kind and evaluate the experimental constraints on the various parameters of this model. We show that the model is consistent with the standard cosmology model for a range of parameters. We then examine possible signatures of the model in certain experiments searching for heavy neutral leptons.

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I Introduction

The experimental measurements of the tau lepton lifetime suggest that it might be a few percent longer than the standard model prediction [1]. One of the simplest ways of obtaining a slightly longer tau lepton lifetime is to assume that the tau neutrino mixes with another neutral particle which is more massive than the tau lepton [2]. Previously we have examined the possibility of implementing this simple idea by adding only a right-handed neutrino to the minimal standard model [3]. We showed that the resulting model is compatible with a longer tau lifetime. In particular we found that to obtain tau lepton lifetime increases over the standard model of more than 1% requires the tau neutrino to have mass greater than 10 MeV. Thus the model will be tested when measurements of the tau neutrino mass improve. Another implication of the model is the prediction of a new heavy neutral Majorana fermion with mass between 120 MeV and 3.5 GeV. A theoretical motivation for this model, and more generally many other models which modify the lepton sector of the standard model, comes from arguments concerning electric charge quantization [4].

In Ref.[3], we made the simplifying assumption of restricting the parameters of the model so that only the third generation mixes with the right-handed neutrino. In this paper we will consider the most general case and examine the experimental bounds on the various mixing parameters. Given these bounds we can then examine the model to see if it is consistent with the standard big bang cosmology model. We then study the heavy neutral Majorana fermion in the model. We will also investigate the possibility that this heavy neutral fermion may show up in double vertex neutrino experiments.

II The tau-lifetime model

The model involves the addition of one gauge singlet Weyl fermion to the standard model. We denote this gauge singlet neutrino as ν_R. Then the most general Yukawa Lagrangian for the lepton sector of this model is

$$\mathcal{L}_{yuk} = \sum_{l=e,\mu,\tau} \lambda_l \bar{f}_{lL} \Phi \nu_{4R} + M \bar{\nu}_{4R} (\nu_{4R})^c + H.c., \tag{1}$$

where

$$f_{lL} = \begin{pmatrix} \nu_{lL} \\ l_L \end{pmatrix} \text{ and } \Phi = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \tag{2}$$

are the usual lepton doublets and Higgs doublet respectively. When the Higgs doublet gains a non-zero vacuum expectation value ($\langle\Phi\rangle = (u, 0)^T$), this Yukawa Lagrangian contains the mass terms:

$$\mathcal{L}_{mass} = 2m\bar{\nu}_{4R}\nu_L + M\bar{\nu}_{4R}(\nu_{4R})^c + H.c., \tag{3}$$

where ν_L is the linear combination of weak eigenstates:

$$\nu_L = \alpha\nu_{eL} + \beta\nu_{\mu L} + \gamma\nu_{\tau L}, \tag{4}$$

with $\alpha = \lambda_e/N$, $\beta = \lambda_\mu/N$, $\gamma = \lambda_\tau/N$, $m = Nu/2$ and $N = \sqrt{\lambda_e^2 + \lambda_\mu^2 + \lambda_\tau^2}$. There are also two orthogonal linear combinations of weak-eigenstates which are orthogonal to ν_L. They are given by

$$\nu_{eL}^0 = \frac{\beta}{\sqrt{1-\gamma^2}}\nu_{eL} - \frac{\alpha}{\sqrt{1-\gamma^2}}\nu_{\mu L},$$

$$\nu_{\mu L}^0 = \frac{\alpha\gamma}{\sqrt{1-\gamma^2}}\nu_{eL} + \frac{\beta\gamma}{\sqrt{1-\gamma^2}}\nu_{\mu L} - \sqrt{1-\gamma^2}\nu_{\tau L}. \tag{5}$$

Note that in this and the remainder of the paper we will denote mass eigenstates by the superscript 0. Clearly, these two combinations are massless from Eq.(3) while the massive state, ν_L, is not a mass eigenstate, but a linear combination of two mass eigenstate fields. The field ν_L gains mass from the terms in Eq.(3) which lead to a 2×2 mass matrix of the form:

$$\mathcal{L}_{mass} = \bar{X}_L \mathcal{M} X_R + H.c., \tag{6}$$

where

$$X_L = \begin{pmatrix} \nu_L \\ (\nu_R)^c \end{pmatrix}, \; X_R = \begin{pmatrix} -(\nu_L)^c \\ \nu_R \end{pmatrix}, \tag{7}$$

and

$$\mathcal{M} = \begin{pmatrix} 0 & m \\ -m & M \end{pmatrix}. \tag{8}$$

Diagonalising this mass matrix, we obtain two mass eigenstate Majorana neutrinos:

$$\nu_L = \cos\phi\,\nu_{\tau L}^0 - \sin\phi(\nu_{4R}^0)^c,$$

$$(\nu_{4R})^c = \sin\phi\,\nu^0_{\tau L} + \cos\phi(\nu^0_{4R})^c, \tag{9}$$

where

$$\tan\phi = \frac{m}{M}. \tag{10}$$

In summary, the addition of a right-handed neutrino singlet to the standard model results in two massless neutrinos, ν^0_e, ν^0_μ, and two massive neutrinos, ν^0_τ, ν^0_4, with their masses given respectively by (assuming $m < M$)

$$\begin{aligned} m_{\nu^0_\tau} &= \frac{m^2}{M}\left[1 + \mathcal{O}\left(\frac{m^2}{M^2}\right)\right], \\ m_{\nu^0_4} &= M\left[1 + \mathcal{O}\left(\frac{m^2}{M^2}\right)\right]. \end{aligned} \tag{11}$$

The corresponding weak eigenstates are related to their mass eigenstates by

$$Y_L = UY^0_L, \tag{12}$$

where

$$Y_L = (\nu_{eL}, \nu_{\mu L}, \nu_{\tau L}, (\nu_{4R})^c)^T \tag{13}$$

and U is the unitary matrix

$$U = \begin{pmatrix} \frac{\beta}{\sqrt{1-\gamma^2}} & \frac{\alpha\gamma}{\sqrt{1-\gamma^2}} & \alpha\cos\phi & -\alpha\sin\phi \\ \frac{-\alpha}{\sqrt{1-\gamma^2}} & \frac{\beta\gamma}{\sqrt{1-\gamma^2}} & \beta\cos\phi & -\beta\sin\phi \\ 0 & -\sqrt{1-\gamma^2} & \gamma\cos\phi & -\gamma\sin\phi \\ 0 & 0 & \sin\phi & \cos\phi \end{pmatrix}. \tag{14}$$

The leptonic charged current interactions are given by

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}}\overline{F_L}\gamma_\mu V Y^0_L W^{-\mu} + H.c., \tag{15}$$

where $F = (e_L, \mu_L, \tau_L)^T$ and V is a 3×4 mixing matrix obtained from U by deleting the last row. For reference we reproduce it below:

$$V = \begin{pmatrix} \frac{\beta}{\sqrt{1-\gamma^2}} & \frac{\alpha\gamma}{\sqrt{1-\gamma^2}} & \alpha\cos\phi & -\alpha\sin\phi \\ \frac{-\alpha}{\sqrt{1-\gamma^2}} & \frac{\beta\gamma}{\sqrt{1-\gamma^2}} & \beta\cos\phi & -\beta\sin\phi \\ 0 & -\sqrt{1-\gamma^2} & \gamma\cos\phi & -\gamma\sin\phi \end{pmatrix}. \tag{16}$$

As will be discussed in section III, the experimental constraints on α and β mean that they have to be quite small (typically less than 0.03). However there are much less severe constraints on $\sin\phi$. The main effect of a non-zero $\sin\phi$ is that the effective coupling of the W boson to the tau lepton is reduced. Note that the range of parameters in the model which give an increase of more than 1% in the tau lifetime corresponds to $\sin\phi$ varying between 0.1 and about 0.3 [3]. In our previous work [3] we have analysed the model in the simplifying case of setting α and β to zero. We have shown that, in this case, to get an increase in the tau lepton lifetime of more than 1% over the standard model prediction requires that the mass of the tau neutrino to be more than 10 MeV. This prediction of the model will either be confirmed or the model ruled out when new measurements of the tau-neutrino mass improve (the current limit is a 35 MeV upper bound [5]). Note that including the effects of non-zero values for α and β will not modify significantly the calculation of the tau neutrino mass since $\alpha, \beta \ll 1$.

The leptonic neutral current interactions for the neutrinos are given by

$$\mathcal{L}_{nc} = \frac{g}{2\cos\theta_W}\overline{Y_L^0}\gamma_\mu A Y_L^0 Z^\mu, \tag{17}$$

where

$$A = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos^2\phi & -\cos\phi\sin\phi \\ 0 & 0 & -\cos\phi\sin\phi & \sin^2\phi \end{pmatrix}. \tag{18}$$

Notice that the neutral current interactions are independent of α and β.

III Experimental bounds on the mixing parameters α, β

The model has two massive Majorana neutrinos ν_τ^0 and ν_4^0. Both of these neutrinos mix with the massless ν_e^0 and ν_μ^0 neutrinos. Neutrino oscillations can occur due to this mixing. The non-observation [6] of such oscillations imply the constraints

$$U_{13} \leq 0.17, \; U_{23} \leq 0.031 \tag{19}$$

A improved bound on U_{13} can be obtained from experiments [7] searching for peaks in the $\pi \to e\nu$ decay:

$$\text{If } 1 \text{ MeV} \leq m_{\nu_\tau^0} \leq 20 \text{ MeV} \;\; \text{then} \;\; U_{13} \leq 0.05,$$

$$\text{If } m_{\nu_\tau^0} \geq 20 \text{ MeV} \quad \text{then} \quad U_{13} \leq 0.003. \tag{20}$$

These bounds can be translated into bounds on α and β in the model. Note that to get a significant (i.e. more than 1%) increase in the tauon lifetime requires $m_{\nu_\tau^0} \geq 10$ MeV and $\cos\phi \approx 1$. Taking this into account and using Eq.(14), we find that Eqs.(19) and (20) give the following bounds on α and β:

$$\begin{gathered} \beta \lesssim 0.031, \\ \alpha \lesssim 0.05 \quad \text{for} \quad m_{\nu_\tau^0} < 20 \text{ MeV}, \\ \alpha \lesssim 0.003 \quad \text{for} \quad m_{\nu_\tau^0} > 20 \text{ MeV}. \end{gathered} \tag{21}$$

If α and β are non-zero, then in addition to neutrino oscillations, other lepton number violating processes [8] such as $\mu \to e\gamma$ can occur. The decay $\mu \to e\gamma$ is radiatively induced at one-loop order in perturbation theory. However since the heavy neutrinos have mass less than about 3 GeV ($\ll M_{W,Z}$), the induced decay rate is heavily suppressed by a type of GIM mechanism, and according to Ref.[9], the branching ratio is

$$B(\mu \to e\gamma) \simeq \frac{3\alpha_{em}}{32\pi}|\alpha\beta|^2 \left(\cos^2\phi \frac{m_{\nu_\tau^0}^2}{M_W^2} + \sin^2\phi \frac{m_{\nu_4^0}^2}{M_W^2}\right)^2 < 10^{-11}|\alpha\beta|^2. \tag{22}$$

The experimental limit on the branching fraction is 5×10^{-11} [10]. By using the bounds from Eq.(21) we see that the theoretical prediction of $\mu \to e\gamma$ is well within the experimental limit.

With the addition of a fourth neutrino one has to check whether this affects the invisible width of the Z boson. In the limit that all the neutrinos have masses much less than the Z boson mass, one can show that the invisible width is the same as that for the case of three neutrinos in the minimal standard model. Since the masses of the neutrinos are all much less than the Z boson mass, the reduction of the invisible Z boson width due to the effects of the finite neutrino mass in the phase space factor is very small.

IV Implications

Having discussed the experimental bound on the various parameters of the model, we now wish to examine two things. The first thing is to see whether the model is consistent with the standard big bang cosmology model (or sometimes called the "party-line cosmology model") [11]. The second thing is to examine possible signatures of the heavy singlet neutrino in neutrino experiments. The most important possible conflict of the model with standard big bang cosmology is that the heavy tau (ν_τ^0) and singlet neutrinos (ν_4^0) will not decay sufficiently rapidly. If they decay too slowly then their presence during the history of the universe will violate the energy density bound. So, to examine the question of whether or not the model is consistent with the standard cosomology model, we have to work out the expected decay rates of the heavy neutrinos.

We start by considering the tau neutrino. The decay of the tau-neutrino, which has mass between 10 and 35 MeV for the case of interest in this model, will proceed via the charged current interaction, i.e.,

$$\nu_\tau^0 \;\to\; e^- \;+\; W^* \;\to\; e^- \;+\; e^+ \;+\; \nu_{e,\mu} \tag{23}$$

The coupling of the ν_τ^0 and e to the W boson can be obtained from Eqs.(15) and (16). For convenience we choose to express the lifetime of the tau neutrino in terms of the muon mass (m_μ) and lifetime (τ_μ) as follows:

$$\tau_{\nu_\tau^0} = \frac{1}{\alpha^2(1-\alpha^2)\cos^2\phi}\left(\frac{m_\mu}{m_{\nu_\tau}}\right)^5 \tau_\mu. \tag{24}$$

For the case of interest, $\cos\phi \approx 1,\ 1-\alpha^2 \simeq 1$ so that the lifetime can be conveniently expressed as

$$\tau_{\nu_\tau^0} \approx \left(\frac{3\times 10^{-3}}{\alpha}\right)^2 \left(\frac{10\ \text{MeV}}{m_{\nu_\tau}}\right)^5 \times 3\times 10^4\ \text{second}. \tag{25}$$

Thus for a significant range of parameters of the model the lifetime of the tau neutrino is compatible with the party-line cosmology bound of 10^4 s [12].

In addition to the tau neutrino there is a heavy neutral fermion, ν_4^0, which is expected to have mass between 120 MeV and 3.5 GeV [3]. Its dominant decay mode is expected to be via the neutral current interaction provided $m_{\nu_4^0} < m_\tau$ [13]. The width due to the neutral current decay mode

$$\nu_4^0 \;\to\; \nu_\tau^0 \;+\; Z^* \;\to\; \nu_\tau^0 \;+\; f \;+\; \bar{f} \tag{26}$$

(with $f = e, \mu, \nu_{e,\mu,\tau}, u, d$) is given by

$$\Gamma(\nu_4^0) = \sum_f \Gamma(\nu_4^0 \to \nu_\tau^0 \bar{f} f) \simeq \frac{G_F^2 m_{\nu_4}^5}{192(2\pi)^3}\cos^2\phi\sin^2\phi\left(21 - 40z + \frac{176}{3}z^2\right), \tag{27}$$

where $z = \sin^2\theta_W$. Note that in the above estimates we have neglected the tauon and quarks heavier than the u and d quarks since they will be either heavily suppressed or forbidden by kinematics. The lifetime of ν_4^0 can be written as

$$\tau_{\nu_4^0} \simeq \frac{8}{\cos^2\phi\sin^2\phi\left(21 - 40z + \frac{176}{3}z^2\right)}\left(\frac{m_\mu}{m_{\nu_4}}\right)^5 \tau_\mu. \tag{28}$$

This may be conveniently re-expressed as

$$\tau_{\nu_4^0} \simeq \frac{2\times 10^{-11}}{\sin^2\phi}\left(\frac{\text{GeV}}{m_{\nu_4^0}}\right)^5 \text{ second.} \tag{29}$$

Hence ν_4^0 has a lifetime which is easily compatible with the party-line cosmology model.

Next, we will proceed to discuss the implications of this model for collider experiments. Since the model has a neutrino (ν_4^0) with a mass around 1 GeV, then one might expect its production and detection in neutrino-nucleon scattering experiments [14] given sufficiently high neutrino beam energies. Indeed, an experiment at Fermilab [15] for example, has been searching for heavy neutral leptons of mass around about a GeV. The idea is that such a lepton would appear in this type of experiment as a double vertex. That is, an almost simultaneous weak interaction separated by some distance in the detector which corresponds to the creation and decay of a heavy neutral lepton.

The heavy neutral lepton ν_4^0 can be produced through either the charged or neutral current interaction. We focus on production via neutral currents since the background from ordinary coincidence weak interaction events is smaller [15, 16]. From the neutral current interactions of Eqs.(17) and (18), we see that only ν_τ^0 couples to ν_4^0. So in order to estimate the number of ν_4^0s produced via the neutral current interaction, we need to know the number of ν_τ^0s in the beam. Here, we are assuming that the neutrinos are produced from pion and kaon decays (as in the case of the Fermilab experiment [15]) so that ν_4^0 is too heavy to be present in the beam. Then the number of ν_τ^0s is given by

$$N(\nu_\tau^0) = \frac{\Gamma(K^+\to\mu^+\nu_\tau^0)}{\Gamma(K^+\to\mu^+\nu_\mu)}N(K^+\to\mu^+) + \frac{\Gamma(\pi^+\to\mu^+\nu_\tau^0)}{\Gamma(\pi^+\to\mu^+\nu_\mu)}N(\pi^+\to\mu^+). \tag{30}$$

This can be rewritten in terms of the neutrino mixing angles as

$$N(\nu_\tau^0) \simeq |U_{23}|^2 N(\mu), \tag{31}$$

where $N(\mu) = N(K^+ \to \mu^+) + N(\pi^+ \to \mu^+)$ is the number of muons produced from the meson decays and hence is also the number of weak eigenstate ν_μs. From this, the number of ν_4^0s produced by neutrino-nucleon scattering normalized to the total number of neutral current interactions N_{NC} is given by [17]

$$\frac{N(\nu_4^0)}{N_{NC}} = |U_{23}|^2 \frac{\sigma(\nu_\tau^0 + N \to \nu_4^0 + X)}{\sigma(\nu_\mu N)_{NC}}, \tag{32}$$

where $\sigma(\nu_\mu N)_{NC}$ is the total neutral current cross section for neutrino-nucleon scattering. The ratio of the cross sections is given by

$$\frac{\sigma(\nu_\tau^0 + N \to \nu_4^0 + X)}{\sigma(\nu_\mu N)_{NC}} \simeq \cos^2\phi \sin^2\phi P(m_{\nu_4^0}), \tag{33}$$

where $P(m_{\nu_4^0})$ is the phase space factor:

$$P(m) = \left(1 - \frac{m^2}{2M_N x E_\nu}\right)^2, \tag{34}$$

(here xE_ν denotes the fraction of neutrino energy transferred during the scattering).

From Eq.(32) we can estimate the number of excess neutral current (at interaction) - neutral current (at decay) (n/n) events relative to that expected in the minimal standard model. This is given by

$$N(n/n) = N(\nu_4^0) Br(\nu_4^0 \to \nu_\tau^0 + Z^*), \tag{35}$$

where the branching fraction $Br(\nu_4^0 \to \nu_\tau^0 + Z^*)$ is

$$\frac{\Gamma(\nu_4^0 \to Z^*)}{\Gamma(\nu_4^0 \to \text{all})} \simeq 1, \tag{36}$$

provided $m_{\nu_4^0} < m_\tau$ [13]. So, as an approximation, if we neglect the phase space factors in Eq.(33) then

$$N(n/n) \simeq \beta^2 \sin^2\phi N_{NC}. \tag{37}$$

This can be as large as $10^{-4} N_{NC}$ for the range of parameters of interest in the model. For the Fermilab experiment [15], $N_{NC} = 5 \times 10^4$, so that $N(n/n) \sim 5$ events. Clearly a larger sample of $\nu_\mu - N$ interactions is required if the singlet neutrino is to be detected.

Note that the production of ν_4^0's will only be distinguishable from ordinary neutral current interactions if the ν_4^0 decays inside the detector. We need to know the decay length, D, which is given by

$$D = |\vec{p}|\tau_{\nu_4^0}/m_{\nu_4^0} \simeq \frac{|\vec{p}|}{\text{GeV}} \frac{5 \times 10^{-3}}{\sin^2\phi} \left(\frac{\text{GeV}}{m_{\nu_4^0}}\right)^6 \text{ metre}, \tag{38}$$

where $\vec{p}$ is the momentum of the neutrino. For our model $\sin^2\phi \sim 10^{-2} - 10^{-1}$ and for a such typical experiment [15], $|\vec{p}| \sim 10^0 - 10^2$ GeV and $D \lesssim 10$ m. Using all this and Eq.(38) we find that the mass of ν_4^0 must be more than about 400 MeV for the particle to be detected in this type of experiment.

V Conclusion

We have examined a simple model which has a longer tauon lifetime than the standard model value. The model is testable since it predicts that the tau neutrino has a Majorana mass of more than 10 MeV. In addition, the model contains a singlet neutrino of mass between 120 MeV and 3.5 GeV (which interacts with the W and Z- bosons via mixing of weak and mass eigenstates). We showed that for a range of parameters the model is consistent with party-line cosmology. We then examined a possible signature for the singlet neutrino in experiments searching for double vertex events. We estimated the number of events in such a typical experiment and conclude that such an experiment may test the model.

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[11] One could argue that the question of consistency of a particle physics theory with the standard cosmology model is not an interesting physical question. This is because by the nature of the subject of cosmology, it is impossible to properly test a cosmology model. The standard cosmology model is quite a simple model and has many successes. However, the model relies on assumptions of physical laws outside their tested domain of validity. It would therefore be unwise to use such a model to *constrain* models of particle physics. Nevertheless, we feel that it is an interesting question to ask whether or not a theory of particle physics is *consistent* with the standard cosmology model. If a theory is inconsistent with some aspects of the standard cosmology model, and the particle physics model is proved correct from experiments, then this will probably lead to a revised and perhaps more successful cosmology theory. It is by testing theories with experiment (and not partyline cosmology) that will lead to an improved understanding of nature.

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be the dominant decay modes for the range of parameters of interest in the model (since to get a significant increase in the tau lepton lifetime requires $\nu_4^0 < 3.5$ GeV). In the case that $m_{\nu_4^0} < m_\tau$, then there will still be some charged current mediated decays. These decays are, however, much suppressed by a factor of α^2 or β^2 with respect to the neutral current ones.

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